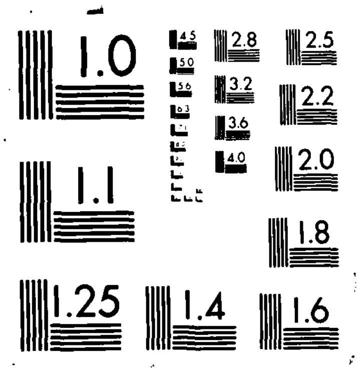
AD-A181 011 THREE DIMENSIONAL STRUCTURE OF TRANSITIONAL BOUNDARY LAYERS(U) ARIZONA STATE UNIV TEMPE W S SARIC 01 MAY 87 AFOSR-TR-87-0739 F49620-85-C-0089 1/1

UNCLASSIFIED F/G 20/4 NL


1.0
4.5
5.0
5.6
6.3
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

UNCLASSIFIED

DTIC FILE COPY

(2)

SECURITY CLASSIFICATION OF THIS PAGE

AD-A181 011

DTIC ELECTE JUN 0 8 1987 S D D

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b.
2a. SECURITY CLASSIFICATION AUTHORITY	3. APPROVED FOR PUBLIC RELEASE DISTRIBUTION IS UNLIMITED
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 87-0739
6a. NAME OF PERFORMING ORGANIZATION ARIZONA STATE UNIVERSITY; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AFOSR/NA
6c. ADDRESS (City, State and ZIP Code) ARIZONA BOARD OF REGENTS, ARIZONA STATE UNIVERSITY, TEMPE, AZ 85287	7b. ADDRESS (City, State and ZIP Code) BUILDING 410, BOLLING AFB, DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR/NA; 8b. OFFICE SYMBOL (If applicable) NA	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F49620-85-C-0089
8c. ADDRESS (City, State and ZIP Code) BUILDING 410, BOLLING AFB, DC 20332-6448	10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
61102F	2307	A2	

11. TITLE (Include Security Classification) (U) THREE DIMENSIONAL STRUCTURE OF TRANSITIONAL BOUNDARY LAYERS

12. PERSONAL AUTHOR(S) WILLIAM S SARIC

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
ANNUAL	FROM 15JUN85 TO 30SEP86	1 MAY 1987	24

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	TRANSITION, BOUNDARY LAYER, STABILITY

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

An overview of research on the three-dimensional nature of bnoundary layer transition conducted at Arizona State University and elsewhere is reviewed in this report. The report reviews the implications of three-dimensionality arising from several sources, including background and free-stream disturbances, curvature, cross-flow and imposed streamwise vorticity.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ XX SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL JAMES M MCMICHAEL	22b. TELEPHONE NUMBER (Include Area Code) 202-767-4935; 22c. OFFICE SYMBOL AFOSR/NA

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

AFOSR-TR- 87-0739

A Year-End Report on

THE THREE-DIMENSIONAL STRUCTURE OF TRANSITIONAL BOUNDARY LAYERS

For the Period

15 June 1985 to 30 September 1986

To

Air Force Office of Scientific Research
Bolling Air Force Base
Washington D.C. 20332

by

William S. Saric
Professor

Mechanical and Aerospace Engineering
Arizona State University
Tempe, AZ 85287

Accesion For	
NTIS CRA&I	☑
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and / or Special
A-1	

ABSTRACT

Within the last five years, increased emphasis on secondary instability analysis along with the experimental observations of subharmonic instabilities have changed the picture of the transition process for boundary layers in low-disturbance environments. Additional efforts with Navier-Stokes computations have formed an impressive triad of tools that are beginning to unravel the details of the early stages of transition. This paper reviews these recent efforts.

SYMBOLS

A	disturbance amplitude
A_o	amplitude at $R=R_o$, usually Branch I
C_p	pressure coefficient
F	$\omega/R = 2\pi f\nu/U_o^2$: dimensionless frequency
f	dimensional frequency [hz]
L	$\sqrt{\nu x^*/U_o}$: boundary-layer reference length.
N	$\ln(A/A_o)$: amplification factor
R	$\sqrt{R_x} = U_oL/\nu$: boundary-layer Reynolds number
R_o	initial boundary-layer Reynolds number, usually Branch I
R_x	U_ox^*/ν : x-Reynolds number or chord Reynolds number
U	basic-state chordwise velocity normalized by U_o
U_o	freestream velocity, [m/s]
W	basic-state spanwise velocity normalized by U_o
x^*	dimensional chordwise coordinate [m]
x	chordwise coordinate normalized with L
y	normal-to-the-wall coordinate
z	spanwise coordinate
α	chordwise complex wavenumber normalized by L
ν	kinematic viscosity [m^2/s]
ω	$2\pi fL/U_o$: dimensionless circular frequency

1. INTRODUCTION

The problems of understanding the origins of turbulent flow and transition to turbulent flow are the most important unsolved problems of fluid mechanics and aerodynamics. There is no dearth of applications for information regarding transition

location and the details of the subsequent turbulent flow. A few examples can be given here. (1) Nose cone and heat shield requirements on reentry vehicles and the "aerospace airplane" are critical functions of transition altitude. (2) Vehicle dynamics and "observables" are modulated by the occurrence of laminar-turbulent transition. (3) Should transition be delayed with Laminar Flow Control on the wings of large transport aircraft, a 25% savings in fuel will result. (4) Lack of a reliable transition prediction scheme hampers efforts to accurately predict airfoil surface heat transfer and to cool the blades and vanes in gas turbine engines. (5) The performance and detection of submarines and torpedoes are significantly influenced by turbulent boundary-layer flows and efforts directed toward drag reduction require the details of the turbulent processes. (6) Separation and stall on low-Reynolds-number airfoils and turbine blades strongly depends on whether the boundary layer is laminar, transitional, or turbulent.

The common thread connecting each of these applications is the fact that they all deal with <u>bounded shear flows</u> (boundary layers) in <u>open systems</u> (with different upstream or initial amplitude conditions). It is well known that the stability, transition, and turbulent characteristics of bounded shear layers are fundamentally different from those of free shear layers (Morkovin, 1969; Tani, 1969; Reshotko, 1976). Likewise, the stability, transition, and turbulent characteristics of open systems are fundamentally different from those of closed systems (Tatsumi, 1984). The distinctions are vital. Because of the influence of indigenous disturbances, surface geometry and roughness, sound, heat transfer, and ablation, it is not possible to develop general prediction schemes for transition location and the nature of turbulent structures in boundary-layer flows.

There have been a number of recent advances in the mathematical theory of chaos that have been applied to closed systems. Sreenivasan and Strykowski (1984), among others, discuss the extension of these ideas to open systems and conclude that the relationship is still uncertain. It appears from a recent workshop and panel discussion (Liepmann et al. 1986) that the direct application of chaos theory to open systems is still some distance away. However, the prospect of incorporating some of the mathematical ideas of chaos into open system problems and of encouraging the transfer of data to the mathematicians is good. Since there is still some uncertainty in the direct application of chaos theory to transition no further mention of this will be given here.

The purpose of this report is to bring into perspective certain advances to our understanding of laminar-turbulent transition that have occurred within the last five years. In particular, these advances have been made by simultaneous experimental, theoretical, and computational efforts.

1.1 Basic Ideas of Transition

With the increased interest in turbulent drag reduction and in large scale structures within the turbulent boundary layer, researchers in turbulence have been required to pay attention to the nature of laminar-turbulent transition processes. It is generally accepted that the transition from laminar to turbulent flow occurs because of an incipient instability of the basic flow field. This instability intimately depends on subtle, and sometimes obscure, details of the flow. The process of transition for boundary layers in external flows can be qualitatively described using the following (albeit, oversimplified) scenario.

Disturbances in the freestream, such as sound or vorticity, enter the boundary layer as steady and/or unsteady fluctuations of the basic state. This part of the process is called receptivity (Morkovin, 1969) and although it is still not well understood, it provides the vital initial conditions of amplitude, frequency, and phase for the breakdown of laminar flow. Initially these disturbances may be too small to measure and they are observed only after the onset of an instability. The type of instability that occurs depends on Reynolds number, wall curvature, sweep, roughness, and initial conditions. The initial growth of these disturbances is described by linear stability theory. This growth is weak, occurs over a viscous length scale, and can be modulated by pressure gradients, mass flow, temperature gradients, etc. As the amplitude grows, three-dimensional and nonlinear interactions occur in the form of *secondary* instabilities. Disturbance growth is very rapid in this case (now over a convective length scale) and breakdown to turbulence occurs.

For many years, linear stability theory, with the Orr-Sommerfeld equation as its keystone, served as the basic tool for predictors and designers. Since the initial growth is linear and its behavior can be easily calculated, transition prediction schemes are usually based on linear theory. However, since the initial conditions (receptivity) are not generally known, only correlations are possible and, most importantly, these correlations must be between two systems with similar environmental conditions. The impossibility of matching or fully understanding these environmental conditions has led to the failure of any absolute transition prediction scheme for even the simple Blasius flat-plate boundary layer.

The preceding is not always follow the observed behavior. At times, the initial instability can be so strong that the growth of linear disturbances is by-passed (Morkovin, 1969) in such a way that turbulent spots appear or secondary instabilities occur and the flow quickly becomes turbulent. This phenomenon is not well understood but has been documented in cases of roughness and high freestream turbulence (Reshotko, 1986). In

this case, transition prediction schemes based on linear theory fail completely.

1.2 Review of the Literature

The literature review follows the outline of the process described above and begins with Reshotko (1984a, 1986) on receptivity (i.e. the means by which freestream disturbances enter the boundary layer). In these papers, Reshotko summarizes the recent work in this area and points out the difficulties in understanding the problem. Indeed, the receptivity question and the knowledge of the initial conditions are the key issues regarding a transition prediction scheme. Of particular concern to the transition problem are the quantitative details of the roles of freestream sound and turbulence. Aside from some general correlations, this is still an opaque area. However. in section 3.2 below, a demonstration of the role of initial conditions on the observed transition phenomenon is discussed.

The details of linear stability theory are given in Mack (1984b). This is actually a monograph on boundary-layer stability theory and should be considered required reading for those interested in all aspects of the subject. It covers 58 pages of text with 170 references. In particular, his report updates the three-dimensional (3-D) material in Mack (1969), covering in large part Mack's own contributions to the area.

The foundation paper with regard to nonlinear instabilities is Klebanoff et al. (1962). This seminal work spawned numerous experimental and theoretical works (not all successful) for the period of 20 years after its publication. It was not until the experimental observations of subharmonic instabilities by Kachanov et al. (1977), Kachanov and Levchenko (1984), and Saric and Thomas (1984), along with the work on secondary instabilities, that additional progress was made in this area. Recent papers of Herbert (1984a,b,c; 1985; 1986a,b) cover the problems of secondary instabilities and nonlinearities i.e. those aspects of the breakdown process that succeed the growth of linear disturbances. It should be emphasized that two- dimensional waves do not completely represent the breakdown process since the transition process is *always* three-dimensional in bounded shear flows. Herbert describes the recent efforts in extending the stability analysis into regions of wave interactions that produce higher harmonics, three-dimensionality, subharmonics, and large growth rates--all harbingers of transition to turbulence. Recent 3-D Navier-Stokes computations by Fasel (1980,1986), Spalart (1984), Spalart and Yang (1986), Kleiser and Laurien (1985, 1986) Reed and co-workers (Singer et al. 1986, 1987; Yang et al. 1987) have added additional understanding to the phenomena. More is said about this in section 3.2.

The paper by Arnal (1984) is an extensive description and review of transition

prediction and correlation schemes for two-dimensional flows that covers 34 pages of text and over 100 citations. An analysis of the different mechanisms that cause transition such as Tollmien-Schlichting (T-S) waves, Gortler vortices, and turbulent spots is given. The effects that modulate the transition behavior are presented. These include the influence of freestream turbulence, sound, roughness, pressure gradient, suction, and unsteadiness. A good deal of the data comes from the work of the group at ONERA/CERT part of which has only been available in report form. The different transition criteria that have been developed over the years are also described which gives an overall historical perspective of transition prediction methods.

In a companion paper, Poll (1984b) extends the description of transition to 3-D flows. When the basic state is three-dimensional, not only are 3-D disturbances important, but completely different types of instabilities can occur. Poll concentrates on the problems of leading-edge contamination and crossflow vortices, both of which are characteristic of swept-wing flows. The history of these problems as well as the recent work on transition prediction and control schemes are discussed. We return to a discussion of 3-D flows in section 4.

Reshotko (1984b, 1985, 1986) and Saric (1985b) review the application of stability and transition information to problems of drag reduction and in particular, laminar flow control. They discuss a variety of the laminar flow control and transition control issues which will not be covered here.

2. REVIEW OF T-S WAVES

The disturbance state is restricted to two dimensions with a one-dimensional basic state. The 2-D instability to be considered is a viscous instability in that the boundary-layer velocity profile is stable in the inviscid limit and thus, an increase in viscosity (a decrease in Reynolds number) causes the instability to occur in the form of 2-D traveling waves called T-S waves. All of this is contained within the framework of the Orr-Sommerfeld equation, OSE. The historical development of this work is given in Mack (1984b) and a tutorial is given by Saric (1985a).

The OSE is linear and homogeneous and forms an eigenvalue problem which consists of determining the wavenumber, α, as a function of frequency, ω, Reynolds number, R, and the basic state, U(y). The Reynolds number is usually defined as $R = U_o L/\nu = (R_x)^{1/2}$ and is used to represent distance along the surface. In general, $L = (\nu x^*/U_o)^{1/2}$ is the most straightforward reference length to use because of the simple form of R and because the Blasius variable is the same as y in the OSE. When comparing the solutions of the OSE with experiments, the dimensionless frequency, F, is

introduced as $F = \omega/R = 2\pi f\upsilon/U_0^2$ where f is the frequency in Hertz.

Usually, an experiment designed to observe T-S waves and to verify the 2-D theory is conducted in a low-turbulence wind tunnel (u'/U_0 from 0.02% to 0.06%) on a flat plate with zero pressure gradient (determined from the shape factor = 2.59 and not from pressure measurements!) where the virtual-leading-edge effect is taken into account by carefully controlled boundary-layer measurements. Disturbances are introduced by means of a 2-D vibrating ribbon using single-frequency, multiple-frequency, step-function, or random inputs (Costis and Saric, 1982) taking into account finite-span effects (Mack, 1984a). Hot wires measure the U + u' component of velocity in the boundary layer and d-c coupling separates the mean from the fluctuating part. The frequency, F, for single-frequency waves remains a constant.

When the measurements of are repeated along a series of chordwise stations, the maximum amplitude of the waves varies. At constant frequency, the disturbance amplitude initially decays until the Reynolds number at which the flow first becomes unstable is reached. This point is called the <u>Branch I</u> neutral stability point and is given by R_I. The amplitude grows exponentially until the <u>Branch II</u> neutral stability point is reached which is given by R_{II}. The locus of R_I and R_{II} points as a function of frequency gives the <u>neutral stability curve</u> shown in Fig. 1. If the growth rate of the disturbances is defined as $\sigma = \sigma(R,F)$, Fig. 1 is the locus of $\sigma(R,F) = 0$. For R > 600 the theory and experiment agree very well for Blasius flow. For R < 600 the agreement is not as good because the theory is influenced by nonparallel effects and the experiment is influenced by low growth rates and nearness to the disturbance source. Virtually all problems of practical interest have R > 1000 in which case the parallel theory seems quite adequate (Gaster, 1974; Saric and Nayfeh, 1977).

By assuming that the growth rate, $\sigma = \sigma(R,F)$, to hold locally (within the quasi-parallel flow approximation), the disturbance equations are integrated along the surface with R = R(x) to give:

$$A/A_0 = \exp(N)$$

where $dN/dR = \sigma$, A and A_0 are the disturbance amplitudes at R and R_I, respectively, and R_I is the Reynolds number at which the constant-frequency disturbance first becomes unstable (Branch I of the neutral stability curve).

The basic design tool is the correlation of N with transition Reynolds number, R_T, for a variety of observations. The correlation will produce a number for N (say 9) which is now used to predict R_T for cases in which experimental data are not available. This is the celebrated *e^N method* of Smith and von Ingen (e.g. Arnal, 1984; Mack, 1984b). The basic LFC technique changes the physical parameters and keeps N within reasonable

limits in order to prevent transition. As long as laminar flow is maintained and the disturbances remain linear, this method contains all of the necessary physics to accurately predict disturbance behavior. As a transition prediction device, the e^N method is certainly the most popular technique used today. It works within some error limits <u>only</u> if comparisons are made with experiments with identical disturbance environments. Since no account can be made of the initial disturbance amplitude this method will always be suspect to large errors and should be used with extreme care. When bypasses occur, this method does not work at all. Mack (1984b) and Arnal(1984) give examples of growth-rate and e^N calculations showing the effects of pressure gradients, Mach number, wall temperature, and three dimensionality for a wide variety of flows. These reports contain the most up-to-date stability information.

3. SECONDARY INSTABILITIES AND TRANSITION

There are different possible scenarios for the transition process, but it is generally accepted that transition is the result of the uncontrolled growth of unstable three-dimensional waves. Secondary instabilities with T-S waves are reviewed in some detail by Herbert (1984b, 1985, 1986), Saric and Thomas (1984) and Saric et al.(1984). Therefore, only a brief outline is given in section 3.1 in order to give the reader some perspective of the different types of breakdown. Section 3.2 discusses the very recent results.

3.1 Secondary Instabilities

The occurrence of three-dimensional phenomena in an otherwise two-dimensional flow is a necessary prerequisite for transition (Tani, 1981). Such phenomena were observed in detail by Klebanoff et al. (1962) and were attributed to a spanwise differential amplification of T-S waves through corrugations of the boundary layer. The process leads rapidly to spanwise alternating "peaks" and "valleys", i.e., regions of enhanced and reduced wave amplitude, and an associated system of streamwise vortices. The peak-valley structure evolves at a rate much faster than the (viscous) amplification rates of T-S waves. The schematic of a smoke-streakline photograph (Saric et al. 1981) in Fig. 2 shows the sequence of events after the onset of "peak-valley splitting". This represents the path to transition under conditions similar to Klebanoff et al. (1962) and is called a *K-type* breakdown. The lambda-shaped (Hama and Nutant, 1963) spanwise corrugations of streaklines, which correspond to the peak-valley structure of amplitude variation, are a result of weak 3-D displacements of fluid particles across the critical layer and precede the appearance of Klebanoff's "hair-pin" vortices. This has been

supported by hot-wire measurements and Lagrangian-type streakline prediction codes (Saric et al.,1981; Herbert and Bertolotti, 1985). Note that the lambda vortices are ordered in that peaks follow peaks and valleys follow valleys.

Since the pioneering work of Nishioka et al.(1975, 1980), it is accepted that the basic transition phenomena observed in plane channel flow are the same as those observed in boundary layers. Therefore, little distinction will be given here as to whether work was done in a channel or a boundary layer. From the theoretical and computational viewpoint, the plane channel is particularly convenient since the Reynolds number is constant, the mean flow is strictly parallel, certain symmetry conditions apply, and one is able to do temporal theory. Thus progress has been first made with the channel flow problem.

Different types of three-dimensional transition phenomena recently observed (e.g. Kachanov et al. 1977; Kachanov and Levchenko, 1984; Saric and Thomas, 1984; Saric et al. 1984, Kozlov and Ramanosov, 1984) are characterized by staggered patterns of peaks and valleys (see Fig.3) and by their occurrence at very low amplitudes of the fundamental T-S wave. This pattern also evolves rapidly into transition. These experiments showed that the subharmonic of the fundamental wave (a necessary feature of the staggered pattern) was excited in the boundary layer and produced either the resonant wave interaction predicted by Craik (1971) (called the *C-type*) or the secondary instability of Herbert (1983) (called the *H-type*). Spectral broadening to turbulence with self-excited subharmonics has been observed in acoustics, convection, and free shear layers and was not identified in boundary layers until the results of Kachanov et al. (1977). This paper re-initiated the interest in subharmonics and prompted the simultaneous verification of C-type resonance (Thomas and Saric, 1981; Kachanov and Levchenko, 1984). Subharmonics have also been confirmed for channel flows (Kozlov and Ramazanov, 1984) and by direct integration of the Navier-Stokes equations (Spalart, 1984). There is visual evidence of subharmonic breakdown before Kachanov et al. (1977) in the work of Hama (1959) and Knapp and Roache (1968) which was not recognized as such at the time of their publication. The recent work on subharmonics is found in Herbert (1985, 1986a,b), Saric, Kozlov and Levchenko (1984), and Thomas (1986).

The important issues that have come out of the subharmonic research is that the secondary instability depends not only on disturbance amplitude, but on phase and fetch as well. Fetch means here the distance over which the T-S wave grows in the presence of the 3-D background disturbances. If T-S waves are permitted to grow for long distances at low amplitudes, subharmonic secondary instabilities are initiated at disturbance amplitudes of less than $0.3\%U_O$. Whereas, if larger amplitudes are introduced, the

breakdown occurs as K-type at amplitudes of $1\%U_0$. Thus, there no longer exists a "magic" amplitude criterion for breakdown.

A consequence of this requirement of a long enough fetch for the subharmonic to be entrained from the background disturbances is that the subharmonic interaction will occur at or to the right of the Branch II neutral stability point (see Fig. 1). Since this is in the stable region of the fundamental wave, it was not likely to be observed because the experimenters quite naturally concentrated their attention of measurements between Branch I and Branch II.

3.2 Recent Results

The surprise that results from the analytical model of Herbert (1986a,b) and the Navier-Stokes computations of Singer, Reed, and Ferziger (1986), is that under conditions of the experimentally observed K-Type breakdown, the subharmonic H-Type is still the dominant breakdown mechanism instead of the fundamental mode. This is in contrast to Klebanoff's experiment, confirmed by Nishioka et al. (1975, 1980),Kachanov et al. (1977), Saric and Thomas (1984), Saric et al. (1984), and Kozlov and Ramazanov (1984) where only the breakdown of the fundamental into higher harmonics was observed. Only Kozlov and Ramazanov (1984) observed the H-type in their channel experiments and only when they artificially introduced the subharmonic.

This apparent contradiction was resolved by Singer, Reed, and Ferziger (1987). Here the full three-dimensional, time-dependent incompressible Navier-Stokes equations are solved with no-slip and impermeability conditions at the walls. Periodicity was assumed in both the streamwise and spanwise directions. The implementation of the method and its validation are described by Singer, Reed and Ferziger (1986). Initial conditions include a two-dimensional T-S wave, random noise, and streamwise vortices. No shape assumptions are necessary, the spectrum is larger, and random disturbances whether freestream or already in the boundary layer can be introduced and monitored for growth and interactions (Singer, Reed, and Ferziger, 1986). Other advantages realized by computations are 1) the inclusion of boundary-layer growth, neglected in linear theory but important to the growth of secondary instabilities, 2)the generation of ensemble averages, 3) the visualization of flow phenomena for comparison with experiments (advanced graphics capability), and 4) the calculation of vorticity and energy spectra, often unavailable from experiments.

The streamwise vortices can alter the relative importance of the subharmonic and fundamental modes. Streamwise vortices of approximately the strength of those that might be found in transition experiments can explain the difficulty in experimentally

identifying the subharmonic route to turbulence (Herbert 1983).

The corresponding computational visualizations of Singer et al. (1987) are shown in Figs. 4 and 5; flow is from lower right to upper left. Figure 4 shows the vortex structures, commonly seen in the transition process, under the conditions of a forced 2-D T-S wave and random noise as initial conditions. The subharmonic mode is present as predicted by theory but not seen experimentally. Other views of the vortical structure are given by Herbert (1986a). However, when streamwise vorticity (as is present in the flow from the turbulence screens upstream of the nozzle) is also included, the subharmonic mode is overshadowed by the fundamental mode (as in the experiments!). The resulting pattern, ordered peak-valley structure, is seen in Fig. 5. Here is a case in which the computations have explained discrepancies between theory and experiments.

In the presence of streamwise vorticity, the fundamental mode is preferred over the subharmonic; this agrees with experimental observations, but not with theory (which does not account for this presence). Without streamwise vorticity, the subharmonic modes dominate as predicted by theory and confirmed by computational simulations. In the presence of streamwise vorticity characteristic of wind-tunnel experiments, the K-type instability dominates and the numerical simulations predict the experimental results.

Direct numerical simulations are playing an increasingly important role in the investigation of transition; the literature is growing, especially recently. This trend is likely to continue as considerable progress is expected towards the development of new, extremely powerful supercomputers. In such simulations, the full Navier-Stokes equations are solved directly by employing numerical methods, such as finite-difference or spectral methods. The direct simulation approach is widely applicable since it avoids many of the restrictions that usually have to be imposed in theoretical models.

The Navier-Stokes solutions are taken hand-in-hand with the wind tunnel experiments in a complementary manner. The example of Singer, Reed, and Ferziger (1987) illustrate that these two techniques cannot be separated. The next step in the simulations will be to predict the growing body of detailed data being developed by Nishioka et al. (1980, 1981, 1984, 1985) on the latter stages of the breakdown process.

4. THREE-DIMENSIONAL BOUNDARY LAYERS

Three-dimensional flows offer a rich variety of instability mechanisms and the 3-D boundary-layer flow over the swept-wing is no exception. This type of flow is susceptible to four types of instabilities that lead to transition. They are leading-edge contamination, streamwise instability, centrifugal instability, and the topic of this section, crossflow instability. Leading-edge contamination occurs along the attachment line and

is caused by disturbances that propagate along the wing edge (Poll 1979, 1984a,b). Streamwise instability is associated with the chordwise component of flow and is quite similar to processes in two-dimensional flows, where T-S waves generally develop. This usually occurs in zero or positive pressure-gradient regions on a wing. The general theory is given by Nayfeh (1980). Centrifugal instabilities occur in the shear flow over a concave surface and appear in the form of Gortler vortices (Floryan and Saric, 1979; Hall, 1983). Attachment-line contamination problems are important for transition control but not discussed here because of the existing reviews cited above. At the same time, a review of Gortler vortices is beyond the goal of this report.

A wide body of literature exists on stability and transition problems of rotating disks, cones, and spheres. These are classic problems of three-dimensional boundary layers that exhibit the same generic stability characteristics. The protagonists are Malik et al. (1981), Kobayashi and Kohama (1984), and Kohama and Kobayashi (1983). These, along with others, are reviewed by Reed and Saric (1986) and will not be discussed here.

The focus of this section is on the crossflow instability which occurs in strong negative pressure gradient regions on swept wings. In the leading-edge region both the surface and flow streamlines are highly curved. The combination of pressure gradient and wing sweep deflects the inviscid-flow streamlines inboard as shown in the schematic of Fig. 6. This mechanism re-occurs in the positive pressure gradient region near the trailing edge. Because of viscous effects, this deflection is made larger in the boundary layer, and causes *crossflow*, i.e. the development of a velocity component inside the boundary layer that is perpendicular to the inviscid-flow velocity vector. This is illustrated in the schematic of Fig. 7. This profile is characteristic of many different three-dimensional boundary-layer flows. The crossflow profile has a maximum velocity somewhere in the middle of the boundary layer, going to zero on the plate surface and at the boundary-layer edge. This profile exhibits an inflection point (a condition which is known to be dynamically unstable) causing so-called crossflow vortex structures to form with their axes in the streamwise direction. These crossflow vortices all rotate in the same direction. Descriptions of this instability are given in the classic paper by Gregory, Stuart and Walker (1955) and in the reports by Mack (1984b) and Poll (1984b).

In the past ten years considerable progress has been achieved in calculating the stability characteristics of three-dimensional flows. The state-of-the-art transition prediction method still involves linear stability theory coupled with an e^N transition prediction scheme (Mack, 1984b; Poll, 1984b). Malik and Poll (1984) extend the stability analysis of three-dimensional flows, analyzing the flow over a yawed cylinder,

to include curvature of the surface and streamlines. They show that curvature has a very stabilizing effect on the disturbances in the flow. This is compared with the experimental results of Poll (1984a) which show good agreement with the transition prediction scheme. They also find that the most highly amplified disturbances are traveling waves and not stationary waves. Here again Malik and Poll (1984) obtain good agreement with Poll's (1984a) recent experimental work where Poll identifies a highly amplified traveling wave around one kHz near transition. Malik and Poll obtain N factors for the fixed-frequency disturbances between 11 and 12 which agreed with the work of Malik, Wilkinson and Orszag (1981) on the rotating disk. In both cases (the disk and cylinder), when the extra terms involving curvature and Coriolis effects are omitted in the stability analysis, the N factors are much larger which illustrates the need to do the realistic stability calculations.

Michel, Arnal and Coustols (1984) develop transition criteria for incompressible two- and three-dimensional flows and in particular for the case of a swept wing with infinite span. They correlate transition onset on the swept wing using three parameters: a Reynolds number based on the displacement thickness in the most unstable direction of flow, the streamwise shape parameter, and the external turbulence level. They simplify the problem by not including curvature effects and assuming locally parallel flow and even with these simplifications, the comparison with experiment shows good agreement.

The current experimental work of Poll (1984a) focuses on the crossflow instability where he shows that increasing yaw has a very destabilizing effect on the flow over a swept cylinder. He characterizes the instability in two ways. The first is by *fixed* disturbances visualized by either surface evaporation or oil-flow techniques. These disturbances are characterized by regularly spaced streaks aligned approximately in the inviscid-flow direction, leading to a "saw-tooth" pattern at the transition location. The second way is with unsteady disturbances in the form of a large-amplitude high-frequency harmonic wave at frequencies near one kHz. At transition near the wall surface, he obtains disturbance amplitudes greater than 20% of the local mean velocity. Initially he tries to use two parameters to predict transition. They are the crossflow Reynolds number and a shape factor based on the streamwise profile. However, based on the results of his research, he found that two parameters alone are not enough to predict transition, and that one needs at least three parameters to accurately describe the crossflow instability.

Michel, Arnal, Coustols and Juillen (1984) present some very good experimental results on the crossflow instability, conducted on a swept airfoil model. By surface visualization techniques they show regularly spaced streaks that are aligned practically in

the inviscid-flow direction, with a "saw-tooth" pattern near the transition area. They perform hot-wire measurements on the stationary waves. Their results show a spanwise variation of the boundary layer before transition that becomes chaotic in the transition region. The variations are damped in the turbulent region. They also find a small peak in the spectra around one kHz (like Poll, 1984a), which is due to a streamwise instability. In addition to this they provide some theoretical work on the secondary velocities, and show counter rotating vortices in the streamwise direction. However, when these components are added to the mean velocities the vortices are no longer clearly visible. Even with all this progress there are very little experimental data with which to compare the theoretical models.

A major unanswered question concerning swept-wing flows is the interaction of crossflow vortices with T-S waves. If the vortex structure continues aft into the mid-chord region where T-S waves are amplified, some type of interaction could cause premature transition. In fact, the unsteadiness at transition observed by Poll and Michel et al. could be due to this phenomenon. Indeed early LFC work of Bacon et al. (1962) show a somewhat anomalous behavior of transition when sound is introduced in the presence of crossflow vortices. It is well known that streamwise vortices in a boundary layer strongly influence the behavior of other disturbances. Nayfeh (1981) shows that Gortler vortices produce a double-exponential growth of T-S waves. Malik (1986) in a computational simulation of the full Navier-Stokes equations is unable to find this interaction however, indicating a need for more work in this area. Herbert and Morkovin (1980) show that the presence of T-S waves produces a double-exponential growth of Gortler vortices, while Floryan and Saric (1980) show a similar behavior for streamwise vortices interacting with Gortler vortices. Reed (1984) analyzes the crossflow/T-S interaction in the leading-edge region by using a parametric-resonance model. Reed shows that the interaction of the crossflow vortices with T-S waves produces a double exponential growth of the T-S waves. The results of Bacon, Pfenninger and Moore (1962) and Reed (1984) clearly show the need to experimentally study problems of this kind.

Saric and Yeates (1985) established a three-dimensional boundary layer on a flat plate that is typical of infinite swept-wing flows. This is done by having a swept leading edge and contoured walls to produce the pressure gradients. The experimentally measured C_p distribution is used along with the 3-D boundary-layer code of Kaups and Cebeci (1977) to establish the crossflow experiment and to compare with the theory. Some of the results of Saric and Yeates (1985) are discussed below because they illustrate that not everything is as it should be in three-dimensional boundary layers.

Boundary-layer profiles are taken at different locations along the plate with both the slant-wire and straight-wire probes. Reduction of both the straight-wire and slant-wire data at one location produces a crossflow profile which provides comparison with the theory. The velocity component perpendicular to the inviscid-flow velocity vector is called the crossflow velocity. By definition, since the crossflow profile is perpendicular to the edge velocity, the crossflow velocity is zero in the inviscid flow.

Disturbance measurements of the mean flow are conducted (Saric and Yeates, 1985) within the boundary layer by making a spanwise traverse (parallel to the leading edge) of the hot wire at a constant y location with respect to the plate. These measurements are carried out at many different x and y locations using two different mean velocities. The results show a *steady* vortex structure with a dominant spanwise wavelength of approximately 0.5 cm. The corresponding spectrum for this disturbance measurement shows a sharp peak at a wavelength of about 0.5 cm, but it also shows a broad peak at a larger wavelength of 1.0 cm, generally at a lower amplitude. The cause of this broad peak at the larger wavelength is explained by the linear-theory predictions (Dagenhart, 1981) for crossflow vortices. This 0.5 cm wavelength does not agree with the flow-visualization results nor with the theoretical calculations of the MARIA code (Dagenhart, 1981).

The naphthalene flow-visualization technique shows that there exists a steady crossflow vortex structure on the swept flat plate. The pattern of disturbance vortices is nearly equally spaced and aligned approximately in the inviscid-flow direction. The wavelength of the vortices is on the scale of 1 cm and this spacing agrees quite well with the calculated wavelength from the MARIA code.

While the flow visualization clearly indicates a spanwise wavelength of 1 cm on the surface. the spectra of the hot-wire measurements show a dominant sharp peak at 0.5 cm and a smaller broad-band peak at 1 cm. This apparent incongruity can be explained with the wave interaction theory of Reed (1985), who uses the actual test conditions of this experiment. Reed shows that it is possible for a parametric resonance to occur between a previously amplified 0.5 cm vortex and a presently amplified 1 cm vortex and that measurements taken near the maximum of the crossflow velocity would show a strong periodicity of 0.5 cm. Moreover, Reed's wall-shear calculations and streamline calculations show the 0.5 cm periodicity dying out near the wall and the 1 cm periodicity dominating. These phenomena are not observed by Michel et al. (1984) who measure phenomena not measured by Poll nor Saric and Yeates.

Two important points need to be emphasized. First, one must, whenever possible, use multiple independent measurements. This was the only way the 0.5 cm and the 1.0

cm vortex structure could be reconciled. Second, the steadiness of the vortex structure in the wind tunnel experiments in contrast to the unsteady predictions of the theory, indicates that some characteristic of the wind tunnel is fixing the vortex structure. This is directly analogous to the biasing of the K-type secondary instability in the flat plate flow. Perhaps some very weak freestream vorticity is providing the fix for the crossflow vortex structure. All of this serves notice that stability and transition phenomena are *extremely* dependent on initial conditions.

5. TRANSITION PREDICTION AND CONTROL

When the recent work on subharmonics is added to the discussion at the end of section 3 on the limitations of the e^N method, one indeed has an uncertainty principle for transition (Morkovin, 1978). Transition prediction methods will remain conditional until the receptivity problem is adequately solved and the bypass mechanisms are well understood. In the mean time, extreme care must be exercised when using correlation methods to predict transition. Additional problems of transition prediction and laminar flow control are discussed by Reshotko (1985, 1986). The main principle of laminar flow control is to keep the disturbance levels low enough so that secondary instabilities and transition do not occur. Under these conditions, linear theory is quite adequate and e^N methods can be used to calculate the effectiveness of a particular LFC device.

The idea of transition control through active feedback systems is an area that has received considerable recent attention (Liepmann and Nosenchuck, 1982; Thomas, 1983; Kleiser and Laurien, 1984, 1985; Metcalfe et al., 1985). The technique consists of first sensing the amplitude and phase of an unstable disturbance and then introducing an appropriate out-of-phase disturbance that cancels the original disturbance. In spite of some early success, this method is no panacea for the transition problem. Besides the technical problems of the implementation of such a system on an aircraft, the issue of three-dimensional wave cancellation must be addressed. As Thomas (1983) showed, when the 2-D wave is canceled, all of the features of the 3-D disturbances remain to cause transition at yet another location. Some clear advantage over passive systems have yet to be demonstrated for this technique.

ACKNOWLEDGEMENTS

The author would like to thank Dr. H. Reed for her helpful comments and for sharing her recent work. The author is also grateful to Dr. T. Herbert for his comments and ideas during our collaboration. This work is supported by the Air Force Office of Scientific Research Contract AFOSR-85-NA-077.

REFERENCES

Arnal D. 1984. Description and prediction of transition in two-dimensional incompressible flow. *AGARD Report No. 709* (Special course on stability and transition of laminar flows) VKI, Brussels.

Bacon, J.W. Jr., Pfenninger, W. and Moore, C.R. 1962. Influence of acoustical disturbances on the behavior of a swept laminar suction wing. Northrup Report NOR-62-124.

Costis, C.E. and Saric, W.S. 1982. Excitation of wave packets and random disturbances in a boundary layer. V.P.I.& S.U. Report No. VPI-E-82.26.

Craik, A.D.D. 1971. Nonlinear resonant instability in boundary layers. *J. Fluid Mech., vol. 50,* 393.

Dagenhart, J.R. 1981. Amplified crossflow disturbances in the laminar boundary layer on swept wings with suction. *NASA TP-1902*.

Fasel, H. 1980. Recent developments in the numerical solution of the Navier-Stokes equations and hydrodynamic stability problems, *Comp. Fluid Dyn.,* (Kollman, Wolfgang, ed.), Hemisphere.

Fasel, H. 1986. Numerical simulation of laminar-turbulent transition. Invited Paper, U.S. National Congress of Applied Mechanics, ASME, June 1986.

Floryan, J.M. and Saric, W.S. 1979. Stability of Gortler vortices in boundary layers. *AIAA Paper No. 79-1497 and AIAA J., vol. 20,* 316.

Floryan, J.M. and Saric, W.S. 1980. Wavelength selection and growth of Gortler vortices. *AIAA paper no. 80-1376 and AIAA J., vol. 22,* 1529.

Gaster, M. 1974. On the effects of boundary-layer growth on flow stability. *J. Fluid Mech., vol. 66,* 465.

Gregory, N., Stuart, J.T. and Walker, W.S. 1955. On the stability of three-dimensional boundary layers with applications to the flow due to a rotating disk. *Phil. Trans. Roy. Soc. Lon., vol. A248,* 155.

Hall, P. 1983. The linear development of Gortler vortices in growing boundary layers. *J. Fluid Mech., vol. 130,* 41.

Hama, F.R. 1959. Some transition patterns in axisymmetric boundary layers. *Phys. Fluids, vol. 2,* 664.

Hama, F.R. and Nutant, J. 1963. Detailed flow-field observations in the transition process in a thick boundary layer. *Proc. 1963 Heat Trans. Fluid Mech. Inst.,* 77.

Herbert, T. 1983. Subharmonic three-dimensional disturbances in unstable plane shear flows. *AIAA Paper No. 83-1759*.

Herbert, T. 1984a. Analysis of the Subharmonic Route to Transition in Boundary Layers. *AIAA Paper No. 84-0009.*

Herbert, T. 1984b. Secondary instability of shear flows. *AGARD Report No. 709* (Special course on stability and transition of laminar flows) VKI, Brussels.

Herbert, T. 1984c. Nonlinear effects in boundary-layer stability. *AGARD Report No. 709* (Special course on stability and transition of laminar flows) VKI, Brussels.

Herbert, T. 1985. Three-dimensional phenomena in the transitional flat-plate boundary layer. *AIAA Paper No. 85-0489.*

Herbert, T. 1986a. Vortical Mechanisms in Shear Flow Transition. *Euromech 199 Colloquium, Direct and Large Eddy Simulation,* Vieweg Verlag.

Herbert, T. 1986b. Analysis of secondary instabilities in boundary layers. Invited Paper, U.S. National Congress of Applied Mechanics, ASME, June 1986.

Herbert, T. and Bertolotti, F.P. 1985. Effect of pressure gradients on the growth of subharmonic disturbances in boundary layers, in Proc. Conf. on Low Reynolds Number Airfoil Aerodynamics, ed. T.J. Mueller, Univ. of Notre Dame.

Herbert, T., Bertolotti, F.P. and Santos, G.R. 1985. Floquet analysis of secondary instability in shear flows. ICASE/NASA Workshop on Stability of Time-Dependent and Spatially Varying Flows, August 19-20, Hampton, VA.

Herbert, T. and Morkovin, M. V. 1980. Dialogue on bridging some gaps in stability and transition research. *Laminar-Turbulent Transition,* ed: R. Eppler and H. Fasel, Springer.

Kobayashi, R. and Kohama, Y. 1985. Spiral vortices in boundary layer transition on a rotating cone. *Proc. 2nd IUTAM Symp. on Laminar-Turbulent Transition,* Novosibirsk.

Kachanov, Yu.S., Kozlov, V.V. and Levchenko, V.Ya. 1977. Nonlinear development of a wave in a boundary layer (in Russian). *Mekhanika Zhidkosti i Gaza,* no. 3, 49.

Kachanov, Yu.S. and Levchenko, V.Ya. 1984. Resonant interactions of disturbances in transition to turbulence in a boundary layer. *J. Fluid Mech., vol. 138,* 209. (in Russian in 1982).

Kaups, K. and Cebeci, T. 1977. Compressible laminar boundary layers with suction on swept and tapered wings. *J. Aircraft, vol. 14,* 661.

Klebanoff, P.S., Tidstrom, K.D. and Sargent, L.M. 1962. The three-dimensional nature of boundary-layer instability. *J. Fluid Mech., vol. 12,* 1.

Kleiser, L. and Laurien, E. 1984. Three-dimensional numerical simulation of laminar-turbulent transition and its control by periodic disturbances.*Proc. 2nd IUTAM Symp. Laminar-Turbulent Transition,* Novosibirsk, USSR.

Kleiser, L. and Laurien, E. 1985. Numerical investigation of interactive transition control. *AIAA Paper No. 85-0566*.

Knapp, C.F. and Roache, P.J. 1968. A combined visual and hot-wire anemometer investigation of boundary-layer transition. *AIAA J., vol.6*, 29.

Kohama, Y. and Kobayashi, R. 1983. Boundary layer transition and the behavior of spiral vortices on rotating spheres. J. Fluid Mech. 137, pp 153-164.

Kozlov, V.V. and Ramazanov, M.P. 1984. Development of finite amplitude disturbances in a Poiseuille flow. *J. Fluid Mech., vol. 147*, 149.

Liepmann, H.W. and Nosenchuck, D.M. 1982. Active control of laminar-turbulent transition. *J. Fluid Mech., vol. 118*, 201.

Liepmann, H., Ghil, M., Newell, A., Roshko, A., and Saric, W. 1986. "Is chaos relevant to shear flows?" Chaotic Motion in Open Flows, UC Institute for Nonlinear Studies Workshop, Lake Arrowhead, California, Feb. 7-9, 1986.

Mack, L.M. 1969. Boundary-layer stability theory. Jet Propulsion Lab. Rpt. 900-277, Rev. A.

Mack, L.M. 1984a. Line sources of instability waves in a Blasius boundary layer. *AIAA Paper 84-0168*.

Mack, L.M. 1984b. Boundary-layer linear stability theory. *AGARD Report No. 709* (Special course on stability and transition of laminar flows) VKI, Brussels.

Malik, M.R. 1986. Wave interactions in three-dimensional boundary layers. AIAA Paper No. 86-1129.

Malik, M.R. and Poll, D.I.A. 1984. Effect of curvature on three-dimensional boundary layer stability. *AIAA Paper No. 84-1672*.

Malik, M.R., Wilkinson, S.P. and Orszag, S.A. 1981. Instability and transition in rotating disk flow. *AIAA J., vol.19*, 1131.

Metcalfe, R.W., Rutland, C., Duncan, J.H. and Riley, J.J. 1985. Numerical simulations of active stabilization of laminar boundary layers. *AIAA Paper No. 85-0567*.

Michel, R., Arnal, D. and Coustols, E. 1984. Stability calculations and transition criteria in two- or three-dimensional flows. *Proc. 2nd IUTAM Symp. on Laminar-Turbulent Transition*, Novosibirsk.

Michel, R., Arnal, D., Coustols, E. and Juillen, J.C. 1984. Experimental and theoretical studies of boundary layer transition on a swept infinite wing. *Proc. 2nd IUTAM Symp. on Laminar-Turbulent Transition*, Novosibirsk.

Morkovin, M.V. 1969. On the many faces of transition. *Viscous Drag Reduction* ed: C.S. Wells, Plenum.

Morkovin, M.V. 1978. Instability, transition to turbulence and predictability.

AGARDograph No. 236.

Morkovin, M.V. 1983. Understanding transition to turbulence in shear layers - 1983. AFOSR Final Report, Contract F49620-77-C-0013.

Nayfeh, A.H. 1980. Three-dimensional stability of growing boundary layers. *Laminar-Turbulent Transition,* ed: R. Eppler and H. Fasel, Springer.

Nayfeh, A.H. 1981. Effect of streamwise vortices on Tollmien-Schlichting waves. *J. Fluid Mech., vol. 107,* 441.

Nishioka, M., Iida, S., and Ichikawa, Y. 1975. An experimental investigation of the stability of plane Poiseuille flow, J. Fluid Mech., 72, pp. 731-751.

Nishioka, M., Asai, M. and Iida, S. 1980. An experimental investigation of secondary instability. *Laminar-Turbulent Transition,* ed: R. Eppler and H. Fasel, Springer.

Nishioka, M., Asai, M. and Iida, S. 1981. Wall phenomena in the final stages of transition to turbulence. Transition and Turbulence, ed. R.E. Meyer, Academic Press.

Nishioka, M. and Asai, M. 1984. Evolution of Tollmien-Schlichting waves into wall turbulence. *Turbulence and Chaotic Phenomena in Fluids,* ed: T. Tatsumi, North-Holland.

Nishioka, M. and Asai, M. 1985. 3-D wave disturbances in plane Poiseuille flow. *Laminar-Turbulent Transition,Vol 2.* ed. V. Kozlov, Springer.

Poll, D.I.A. 1979. Transition in the infinite swept attachment line boundary layer. *Aeronautical Quart.,vol. XXX,* 607.

Poll, D.I.A. 1984a. Some observations of the transition process on the windward face of a yawed cylinder. Cranfield College of Aeronautics Report 8407.

Poll, D.I.A. 1984b. Transition description and prediction in three-dimensional flows. *AGARD Report No. 709* (Special course on stability and transition of laminar flows) VKI, Brussels.

Reed, H.L. 1984. Wave interactions in swept-wing flows. *AIAA paper no. 84-1678.*

Reed, H.L. 1985. Disturbance-wave interactions in flows with crossflow. *AIAA Paper No. 85-0494.*

Reed, H.L. and Saric, W.S. 1986. Stability and transition of three-dimensional flows. Invited Paper, U.S. National Congress of Applied Mechanics, ASME, June 1986.

Reshotko, E. 1976. Boundary-layer stability and transition. *Ann. Rev. Fluid Mech. 8,* 311.

Reshotko, E. 1984a. Environment and receptivity. *AGARD Report No. 709* (Special course on stability and transition of laminar flows) VKI, Brussels.

Reshotko, E. 1984b. Laminar flow control - Viscous simulation. *AGARD Report No. 709* (Special course on stability and transition of laminar flows) VKI, Brussels.

Reshotko, E. 1985. Control of boundary-layer transition. *AIAA Paper No. 85-0562.*

Reshotko, E. 1986. Stability and Transition, how much do we know? Invited Paper, U.S. National Congress of Applied Mechanics, ASME, June 1986.

Saric, W.S. 1985a. Boundary-layer transition: T-S waves and crossflow mechanisms. *Proc. AGARD Special Course on Aircraft Drag Prediction and Reduction,* VKI, Belgium, May 1985.

Saric, W.S. 1985b. Laminar flow control with suction: theory and experiment. *Proc. AGARD Special Course on Aircraft Drag Prediction and Reduction,* VKI, Belgium, May 1985.

Saric, W.S., Carter, J.D. and Reynolds, G.A. 1981. Computation and visualization of unstable-wave streaklines in a boundary layer. *Bull. Amer. Phys. Soc., vol.26,* 1252.

Saric, W.S., Kozlov, V.V. and Levchenko, V.YA. 1984. Forced and unforced subharmonic resonance in boundary-layer transition. *AIAA Paper No. 84-0007.*

Saric, W.S. and Nayfeh, A.H. 1977. Nonparallel stability of boundary layers with pressure gradients and suction. *AGARD C-P No. 224*, 6.

Saric, W.S. and Thomas, A.S.W. 1984. Experiments on the subharmonic route to transition. *Turbulence and Chaotic Phenomena in Fluids,* ed: T. Tatsumi, North-Holland.

Saric, W.S. and Yeates, L.G. 1985. Experiments on the stability of crossflow vortices in swept-wing flows. *AIAA Paper No. 85-0493.*

Singer, B.A., Reed, H.L. and Ferziger, J.H. 1986. Investigation of the effects of initial disturbances on plane channel transition. *AIAA Paper No. 86-0433.*

Singer, B.A., Reed, H.L., and Ferziger, J.H. 1987. Effect of streamwise vortices on transition in plane channel flow, accepted,1987 AIAA Aerospace Sciences Meeting, Reno.

Spalart, P. and Yang, K.S. 1986. Numerical simulation of boundary layers. Part 2. Ribbon-induced transition in Blasius flow, accepted Journal of Fluid Mechanics.

Spalart, P.R. 1984. Numerical simulation of boundary-layer transition. *NASA TM-85984.*

Sreenivasan, K.R. and Strykowski, P.J. 1984. On analogies between turbulence in open flows and chaotic dynamical systems, *Turbulence and Chaotic Phenomena in Fluids* (Tatsumi, T., ed.), IUTAM Proc., Kyoto, Japan, Sept. 5-10, 1983.

Tani, I. 1969. Boundary layer transition. *Ann. Rev. Fluid Mech. 1,* 169-196.

Tani, I. 1981. Three-dimensional aspects of boundary-layer transition. *Proc. Indian Acad, Sci., vol. 4,* 219.

Tatsumi, T. (ed.) 1984. *Turbulence and Chaotic Phenomena in Fluids.* Proc. IUTAM

Symp., Kyoto, Japan, Sept. 5-10, 1983.

Thomas, A.S.W. 1983. The control of boundary-layer transition using a wave superposition principle. *J. Fluid Mech., vol. 137,* 233.

Thomas, A.S.W. 1986. Experiments on secondary instabilities in boundary layers. Invited Paper, U.S. National Congress of Applied Mechanics, ASME, June 1986.

Thomas, A.S.W. and Saric, W.S. 1981. Harmonic and subharmonic waves during boundary-layer transition. *Bull. Amer. Phys. Soc., vol. 26,* 1252.

Yang, K.S., Spalart, P.S., Reed, H.L., and Ferziger, J.H. 1987. Navier-Stokes computations of pressure-gradient effects on transition in a boundary layer, accepted: *IUTAM Symposium on Turbulence Management and Relaminarization,* Bangalore, India, 19-23 January.

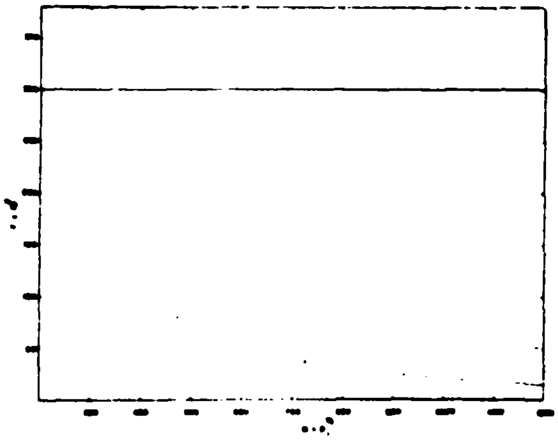


Figure 1 Neutral stability curve for Blasius boundary layer from parallel stability theory

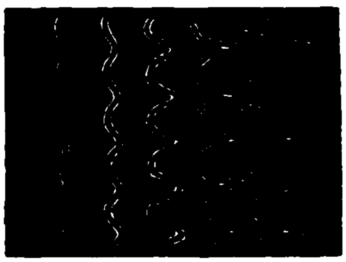


Figure 2 Streaklines in the boundary layer from flow visualization reproduced by Herbert et al 1985 Ordered peak-valley structure of lambda vortices K-Type

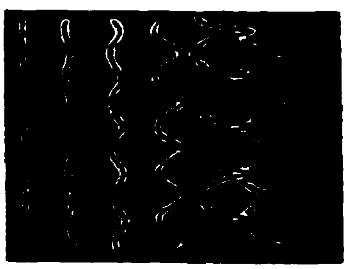


Figure 3 Streaklines in the boundary layer from flow visualization reproduced by Herbert et al 1985 Staggered peak-valley structure of lambda vortices H-Type

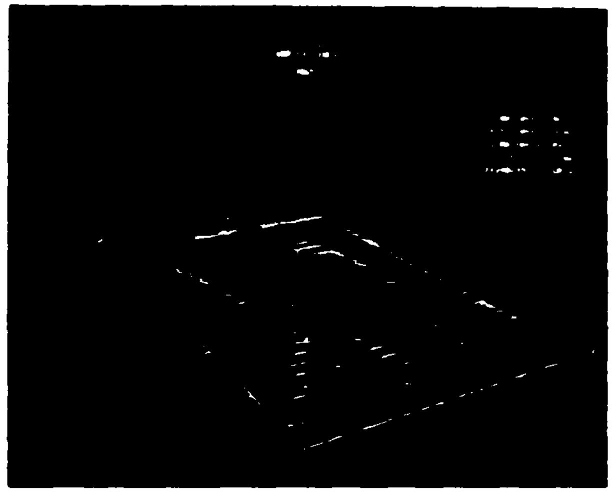


Figure 4 Computer visualization of vortex lines by Singer et al 1987 No imposed streamwise vortices H-Type

Figure 5 Computer visualization of vortex lines by Singer et al 1987 Imposed streamwise vortices K Type

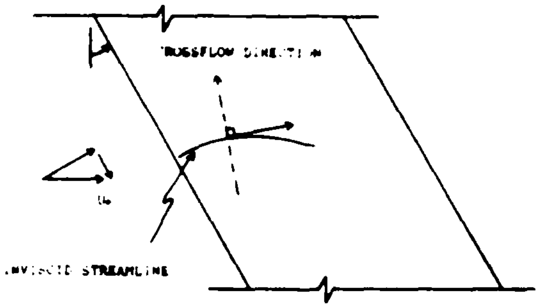


Figure 6 Schematic of flow over a swept wing

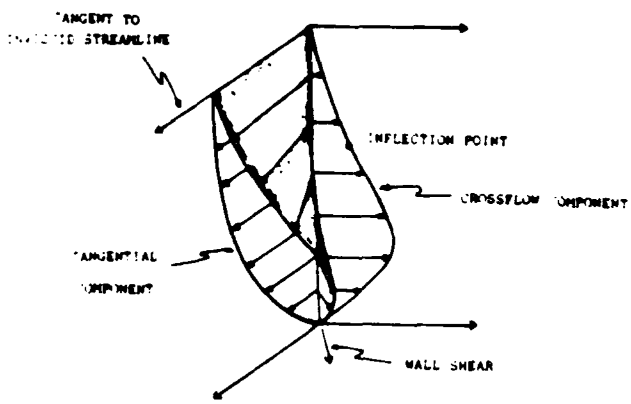


Figure 7 Schematic of velocity components on a swept wing illustrating the definitionof crossflow velocity

END

7-81

DTIC